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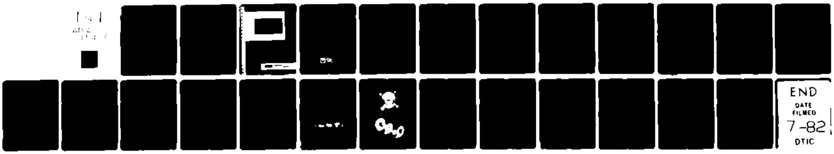

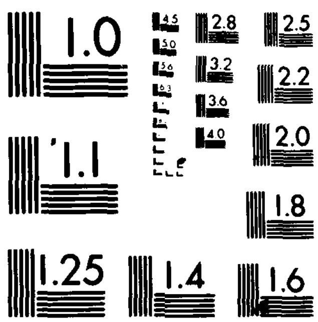

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A literature survey of velocity coupling found that existing analytical models do not predict instability reliably. Manifestations of velocity coupling in burners and motors are described in the literature as harmonic content and mean shift in pressure traces, and susceptibility to triggering instability by pulsing. Evidence of these phenomena were found in numerous laboratory burners, research motors, and development motors. The motors which exhibited velocity coupling all had a large L/D ratio. The severity of instability was found to depend on the propellant composition,

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grain geometry, nozzle geometry, and propellant conditioning temperature. A cold flow simulated rocket motor with porous walls has been constructed. Oscillatory heat flux at the wall has been measured in this simulated motor while driving pressure oscillations with a rotating valve.

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R. S. Brown and R.C Waugh

UNITED TECHNOLOGIES CHEMICAL SYSTEMS

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

Coupling between velocity oscillations and the combustion zone can be significant in determining the acoustic stability of solid propellant rocket motors. Observations of nonlinear wave behavior, pulsed instabilities in motors and laboratory burners, and shifts in mean pressures have been used to formulate qualitative heuristic models for this coupling. Attempts to quantify these models have been unsuccessful in the sense that scaling laboratory results to motor environments have produced conflicting results. Hence, the basic mechanisms have not been clarified by these models. A further review of studies on flow fields in chambers and on acoustics in ducts suggests that these coupling phenomena include the effects of acoustic disturbances on turbulence in flows with high surface transpiration rates, acoustic streaming in the presence of combustion, and unsteady heterogeneous combustion processes. These processes involve fluid-dynamic and combustion-related phenomena which in themselves have not been studied qualitatively.

The objective of the experimental aspects of this program is to investigate the interaction of unsteady oscillatory flow phenomena with the propellant combustion processes. After a review of related motor and laboratory data, initial experiments have been directed toward measuring the effect of acoustic velocity on the radial and axial profiles of the time average velocity and turbulence and on the surface heat flux. To make these measurements, a cold flow apparatus was constructed to simulate the internal flow field in the combustor. Nitrogen flowing through large porous bronze tubes simulates the flow of gas from the propellant surface. The overall length and nozzle throat diameter can be adjusted to permit the effects of propellant burning rate and motor length-to-diameter ratio to be investigated. A rotating valve at the nozzle exhaust plane provides a means of generating acoustic oscillations at a controlled frequency. Specific experimental studies described herein address the effect of acoustic disturbances on turbulence profiles and surface heat flux. The effects of motor length, surface Mach number, and amplitude and frequency of the acoustic oscillations are the primary variables. The specific test conditions and interpretation of the results are being closely coordinated with personnel at Princeton Combustion Research Laboratories, who are currently conducting analytical studies on this problem.

2.0 SURVEY OF LITERATURE

The objective of this literature survey is to review data from motors and burners which show significant contributions from velocity coupling. A number of references were found in which earlier literature searches were performed. Rosen[1] covers solid rocket motor experimental research before 1970. Price[2] describes the experiences of early motor development programs with combustion instability. Price then updated his earlier review to include motor programs during the sixties. CPIA published a bibliography[3] covering combustion instability during the seventies and one covering efforts to measure a velocity coupled response function. Beckstead[4] and Micheli[5] reported reviews in contracted work on velocity coupling in solid rocket motors performed in the mid-seventies.

Beckstead[6] reported on a recent JANNAF workshop in which velocity coupling was defined as the response of a burning propellant surface to local velocity. Two models are currently used to describe velocity coupling, a linear model and a nonlinear model. Lovine[7] summarized these models and included them in a stability prediction computer code which is used throughout the industry for predicting the stability of solid rocket motors. The nonlinear model requires knowledge of a threshold parameter. To date no satisfactory method has been found for evaluating this parameter so the linear model is generally used in quantitatively evaluating motors and propellants with respect to velocity coupling. Dehority and Price[8] described the use of the nonlinear model to qualitatively explain the stability behavior of tactical motors. Though both of these models have been extrapolated to three dimensions, they are based on one dimensional kinematic concepts. Glick[9] discussed some fundamental inadequacies of these models and the problem in applying them to predict motor stability behavior. Also, Brown[10] reported results from the IUS program in which unstable behavior was predicted early in the burn of the small motor and marginal stability was predicted for the large motor. Both of these motors proved to be very stable. Velocity coupling was a large component in the prediction for both of these motors. Glick[11] reported large discrepancies between stability predictions and motor behavior on the STAR motors. Clearly, better models are required for velocity coupling.

In the JANNAF workshop mentioned earlier, Beckstead[6] suggested that the most prominent manifestations of velocity coupling in motors are: 1) sharp-fronted non-sinusoidal waves, 2) a DC shift in the mean pressure, and 3) susceptability to pulsing. It was also noted that these manifestations only occur if a motor is unstable. In current rocket motor stability theory,[7] the stability of a motor is the sum of the contributions of many mechanisms, one of which is velocity coupling. Based on this theory, a motor may have a very significant velocity coupling contribution but be stable because of other stabilizing influences in the motor, and therefore show no manifestations of this velocity coupling in the motor pressure trace.

Though it was not stated, the JANNAF workshop[6] was primarily concerned with axial mode oscillations. The role of velocity coupling in tangential mode oscillations is not directly addressed. Based on current models, cancellation effects in many grain geometries produce no net driving as a result of velocity coupling. However, these models may not be correct and hence in general, there is no reason to exclude velocity coupling as a contribution to tangential mode instability. However, non-sinusoidal steep-fronted wave forms would not be expected for tangential mode oscillations.[12] From a pressure trace alone, there is little basis to discriminate between tangential mode oscillations in which velocity coupling dominates, and tangential mode oscillations in which pressure coupling dominates. This review covers only longitudinal oscillation.

2.1 OVERVIEW OF LABORATORY BURNERS

Several laboratory burners have been constructed specifically to study velocity coupling. Stepp,[13] Beckstead,[4] and Micheli[5] have described the use of the T-burner to measure a velocity coupling response. The results of these programs demonstrate the existence of velocity coupling in that driving was obtained that could not be explained by pressure coupling alone. Harmonic content in the pressure traces was a persistent problem, although the source of these harmonics is not entirely clear. Lyon[14] constructed a variation on the T-burner, using the Helmholtz resonator principle, to measure the velocity coupled response function at low frequency. McDaniel[15] described the use of a sonic end vent burner for measuring the velocity coupling response. Again the existence of velocity coupling seems clear and harmonics were also obtained in the pressure

traces. Brown[16] constructed a dual rotating valve which generates velocity oscillations while minimizing pressure oscillations. The combustion process responded to these velocity oscillations and harmonics were seen on the pressure traces. Micci[17] constructed a modulated throat motor with a full-length grain. Values of a linear velocity coupling response were extracted from data from this motor. Under some conditions a severe instability was initiated in the modulated throat motor with mean pressure shifts and harmonics.[18]

2.2 RESEARCH MOTOR PROGRAMS

Research programs at CARDE,[19,20] SRI[21] and NWC[22] studied pulsed axial mode instability in long slender motors. This form of instability has the three characteristics of velocity coupling described earlier. This work was reviewed by Beckstead[4] but deserves repeating. In the work at CARDE and SRI, it was found that for a given motor and composite propellant, susceptability to pulsed instability increased as the nozzle throat area was decreased. Above some critical $K_n = S_b/S_t$, the motor was always unstable to a head-end pulse; below this critical value the motor was always stable. It was found that for a given K_n in a CP grain; a geometrically similar but smaller motor was more unstable than a larger one. In varying the propellant, higher burn rate propellants were found to be generally, though not always, more stable. The CARDE work used PU and CTPB based composite propellants. Hughes[23] extended this technique to HTPB propellants. The SRI work used a variety of composite systems including KP, AP, LiP and AN oxidizers with PU, PBAN, and PS binders. Two double-base propellants tested at SRI behaved differently than the composite propellants. These propellants were unstable when pulsed at low pressure and stable at high pressure. At SRI a slab motor with 5 pressure transducers equally spaced along the motor length was fired. These data show waves traveling along the motor length. The interpretation of such waves using a linear standing wave analysis troubles some investigators.

The NWC study used a full CP grain with the nozzle in the center rather than at the end; the ARPA motor. A pulsing unit was provided at one end, while a high response and an intermediate response pressure transducer were located on the

other end. Ten different composite propellant were tested in this motor at several different pressures and all were unstable. However, their behavior differed significantly.

There appears to be at least two forms of instability in the ARPA motor which are described as "mild" and "severe". The mild form had nearly sinusoidal wave form and no mean pressure shift. The severe form had high harmonic content and mean pressure shift. Each propellant was rated with respect to: mild form amplitude, severe form amplitude and relative mean pressure shift during severe form. The rankings with respect to these three properties were not necessarily correlated. Some propellants did not become severely unstable until pulsed. Aluminum particle size significantly affected the stability. The stability characteristics were quite pressure-dependent with some propellants; but no generalization can be made because the trends were not the same for all propellants, nor for all aspects of instability.

The results of the NWC tests do not follow the same trends as the tests at CARDE and SRI. For example, in the end vent tests severity of instability increased as the motor pressure was increased. No such consistent trend was seen in the center-vent tests.

2.3 MOTOR EXPERIENCES

Axial mode instability has also been encountered in the following motor and propellant development program: 2.75 FFAR, ATR, ARROW, CHAPARRAL, MK36, MK56, MK17, SUBROC and TARTAR, and a reduced smoke air launched motor. All these motors have a relatively large L/D ratio. Some were stable until pulsed. Others were spontaneously unstable, but were not necessarily consistently unstable from test to test. Following is more detail on the stability history of the motors listed above.

2.3.1 2.75 Motor

This motor is 2.75-in.-diameter and about 27-in. long. Several instances of axial mode instability were found in tests of variations of this motor. The tests conducted at Aerojet with an aluminized propellant in 1967 and 1968[5] showed low amplitude 600 Hz oscillations during the first second of firing.

The data were derived from slow speed records which were not intended for analyzing oscillatory data. A 3% mean pressure shift was estimated during these oscillations. Later tests using a modified grain (a circular port with a flare at the aft end) showed occasional thrust oscillations at 800 Hz, along with a large shift in mean thrust.[5] This motor also used an aluminized propellant. Unfortunately, chamber pressure was not measured on these tests.

This same motor design (CP with aft flare) was used as a demonstration motor in a program[24] to develop smokeless HTPB composite propellants. This motor/propellant combination was unstable in the axial mode at ambient temperature when pulsed and spontaneously unstable at 165°F. Stable burning was obtained with a modified propellant containing additives that are normally used to suppress high frequency tangential mode oscillations. It was concluded that the axial mode instability resulted from tangential mode oscillations which were observed just prior to the longitudinal oscillations. Stability analysis of the fundamental axial mode, using T-burner pressure coupled response data, indicates this mode should have been stable. Linear velocity coupling was predicted to be very small in this grain design.

Haymes described a motor 2.75-in.-diameter designed to produce a dual thrust characteristic. This motor had severe instability in the axial mode at 650 Hz when fired at 140°F. Oscillations generally began in the transition from boost to sustain and were accompanied by a mean pressure shift and harmonics. The motor used an HTPB composite propellant with 16% aluminum and a grain having a circular port in the head end and a four-spoked wagon wheel in the aft end.

Crump reported tests of the 2.75 motor using two different minimum smoke composite propellants. Two grain designs were tested; a circular port and a circular port with a flare at the aft end along with single-port and four-port nozzles. Static and flight tests were made. Motors with the four-port nozzles and circular-port grain were stable. The single-port nozzle was found to be destabilizing. These motors were not artificially pulsed. The instabilities occurred in the axial mode and had large mean pressure shifts, suggesting velocity coupling.

Hughes[23] fired 2.75 motors with three different grain designs and three different smokeless composite propellant formulations. The formulations varied only in the oxidizer particle size distribution and the concentration of burning rate catalyst. The pulses were programmed at several burn times to evaluate the time at which the motor could first be pulsed unstable. The susceptability to instability was found to be inversely proportional to the propellant burn rate. No consistent correlation was found between the susceptibility to instability and the shape of the grain cross-section. The pulse tended to grow faster when initiated later in the firing

2.3.2 ATR

Demuth, et al.[24] used an ATR demonstration motor to develop smokeless composite propellants. Thirty-four motors (16 with a 3 blade aft finocyl grain and 18 with a tapered dogbone grain) were fired using 9 different propellants.

With the dogbone grain, only one test had axial mode oscillations. This particular test at -65°F had two pulses; the first being stable but the second resulting in nonlinear axial oscillations with a mean pressure shift. Interestingly, a comparison motor, which differed only by being conditioned at +165°F, developed tangential mode oscillations but no axial mode oscillations. Several motors with the finocyl grain, using a variety of propellants, had sinusoidal axial mode oscillations and no mean pressure shift.

2.3.3 ARROW

The ARROW[5] was a motor developed by Aerojet for Northrup as part of the SEAS program. An early version used a 4 bladed aft finocyl grain, 3.4 by 31 inches and had axial mode oscillations with a large mean pressure shift. Modifications to the fins improved the stability and eliminated the large mean pressure shift, though oscillations still occurred. An alternative dogbone grain design was developed for this motor. This change eliminated the axial mode oscillations but produced tangential mode oscillations, which were then eliminated by changing the propellant formulation.

2.3.4 CHAPARRAL

Herty tested a low smoke HTPB propellant in a motor having a 5-in. diameter port with an estimated axial mode frequency of about 300 Hz. Three motors were fired and were all stable. The low smoke propellant had a higher burn rate than the propellant it replaced, so 2 of the tests were fired using a larger nozzle area. One of the tests with the larger nozzle area was conditioned at 165°F. All 3 motors were stable and none were pulsed.

Crump reports results from motor tests using 2 minimum smoke composite propellant. None of these motors was artificially pulsed, but several motors produced severe axial mode oscillations. Instability occurred with both propellants, but the propellant composition and the grain design had observable effects on stability. It was concluded that the linear velocity coupling model[7] could explain the results of these tests.

2.3.5 MK36

Kruse[25,26] conducted 16 tests on various versions of a reduced smoke MK36 motor. None of these motors were spontaneously unstable but most were pulsed into axial mode instability at 320 Hz. Variations were made in: the nozzle configuration, the oxidizer size distribution, grain design and conditioning temperature. All of the above parameters were found to have an influence on the motor stability. The authors felt the observed stability behavior can be explained as nonlinear instability in which velocity-coupled driving is a large contributor.

2.3.6 MK56

The MK56 is a dual thrust motor which has encountered pulsed axial mode instability during sustain.

2.3.7 MK17

Some configurations used during motor development of the MK17 exhibited steep-fronted pressure waves.

2.3.8 SUBROC

The SUBROC[27] is about 20 in. in diameter and 120-in. long and used an aluminized polyurethane composite propellant. The grain cross-section was a 6-pointed

star. Oscillations occurred sporadically in the early development of this motor. The oscillations had a basic frequency of 180 Hz with a high harmonic content. The mean pressure increased by about 50% during these oscillations. The oscillations were eliminated by changing the size of the aluminum particles in the propellant.

2.3.9 TARTAR

The TARTAR[28] is a dual concentric grain boost-sustain type motor, about 13 in. in diameter. The sustain propellant is AP, nitroguanidine, and polyurethane. In a program to improve the performance of this motor, resonant burning at 270 Hz was encountered which produced sustain pressure levels two and three times higher than the nominal level. Moving the nozzle throat from the upstream end of the blast-tube to the downstream end minimized the oscillations. Later, during a product improvement program, oscillations were again encountered during sustain. Several mechanical "fixes" were incorporated to eliminate the problem. These "fixes" were all aimed at damping longitudinal oscillations and minimizing the possibility of ejecting material from the motor.

2.3.10 Reduced Smoke Air Launched Motor

Roys and Kruse[29] described the results of testing an advanced air-to-ground missile motor with reduced smoke HTPB propellant. The grain was a 5-bladed forward finocyl with a cone at the aft end. Eleven of these 4-in. diameter motors were fired to test variations in propellant composition and conditioning temperature. The formulations all had nearly the same burn rate. The motors were pulsed twice in each run, once early in the run and once late in the run. All motors were stable to the first pulse. The second pulse generated 500 Hz oscillations in six motors. The pressure traces during the instability had a lot of harmonic content but there was no mention of mean pressure shifts. The variation in stability was attributed, in part at least, to variation in the erosion of the nozzle due to variation in content of ZrC. Authors felt the results are in general agreement with linear stability theory for velocity coupling.

2.4 SUMMARY

In summary velocity coupling refers to the relation between propellant burn rate and the gas velocity in a motor. There are two analytical models for velocity coupling, linear and nonlinear. The linear model is used quantitatively to describe velocity coupling and the nonlinear model is used to explain some aspects of motor behavior. Neither model appears to satisfactorily describe velocity coupling, and motor stability predictions using the linear model have not proved to be accurate. Evidence for the existence of velocity coupling is seen in the behavior of research burners. Long slender research motors exhibit pulsed axial mode instability as do many development motors. It is not always clear how this form of instability is related to velocity coupling.

3.0 EXPERIMENTAL STUDIES

The primary objective of the cold flow experiments is to determine the effect of velocity oscillations on the flow properties in a simulated rocket motor cavity. The derived data will provide direct evidence of the dominant velocity-coupling mechanisms for use in conjunction with the analytical studies. Thus, the experiments need to be conducted concurrently with the analytical studies. Comparisons between the analytical results and the experimental data will be made to guide the analyses and to determine additional critical experiments for defining mechanisms.

3.1 APPARATUS DESCRIPTION

To conduct these experiments, the apparatus shown schematically in figure 1 has been fabricated. Nitrogen flowing through porous cylindrical bronze tubes simulates the combustion process at the propellant surface (this technique has been used successfully in previous studies at CSD on the effects of both steady-state[30,31] and oscillatory characteristics[32] on the internal ballistics). A flow distribution tube is used to equalize the flow to the 4-in. internal diameter porous tubing from the N_2 supply system. Sonic flow is achieved either through this distribution tube or by orifices in the manifold to each section. Figure 2 and 3 show the construction of each section.

Each section is equipped with two ports for heat flux gages (as shown in figure 3) or for hot wire anemometers. Pressure taps are also located at these axial stations on the "grain" surface and one tap is located between the porous tubing and the flow distribution tubing. These taps lead to a scanivalve/pressure transducer multiplexing system for recording the mean pressure distribution throughout the apparatus. Kistler tranducers are mounted at both the head-end and aft-end of the apparatus. The hot wire anemometers and the hot film flux gages are connected to TSI Model 1050 signal conditioners. By operating in the constant current mode, frequencies up to 10 kHz can be recorded faithfully.

The simulator is equipped with a rotating valve at the aft-end to generate acoustic velocity oscillations. The frequency is controlled by varying the rotational speed of the electric motor driving the valve. Figure 4 shows an

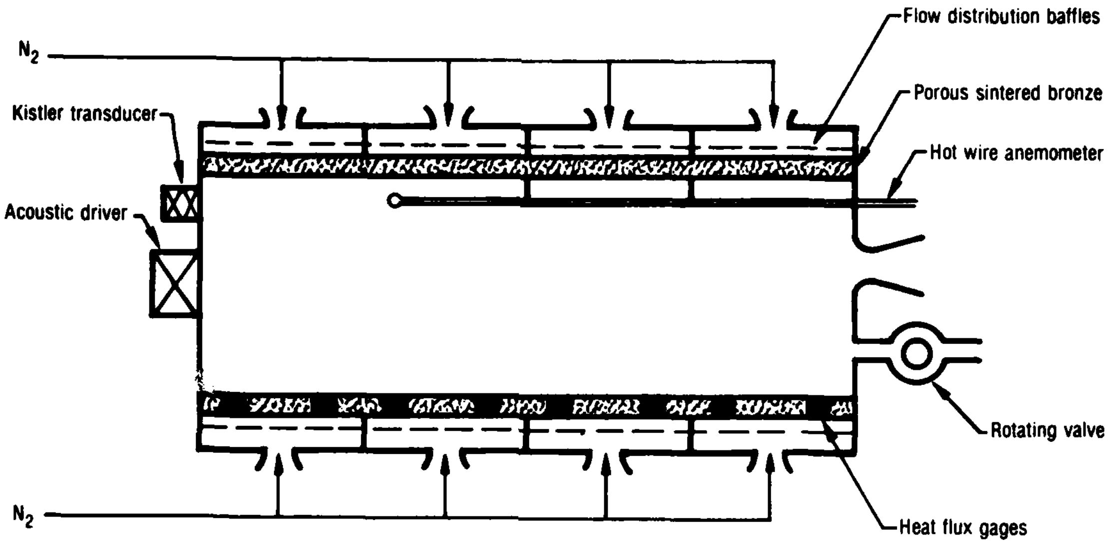

Figure 1. Cold Flow Velocity-Coupling Apparatus

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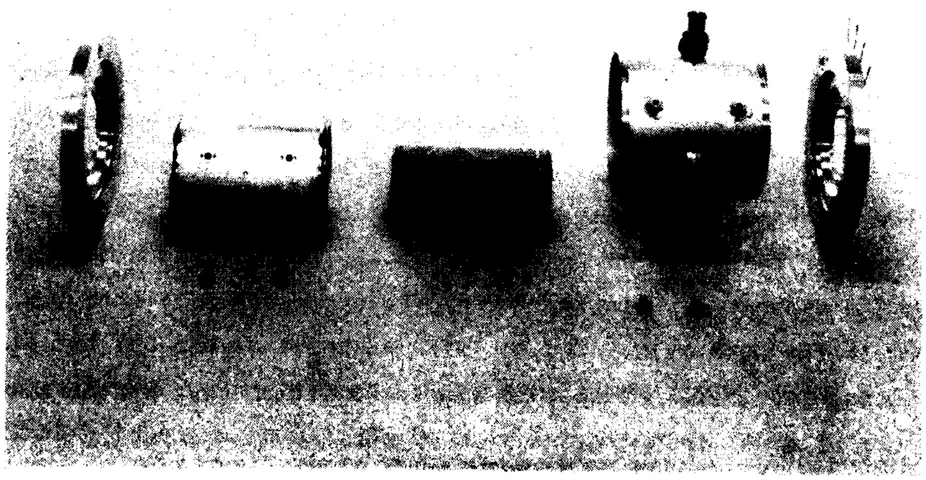

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Figure 2. Exploded View of Segment

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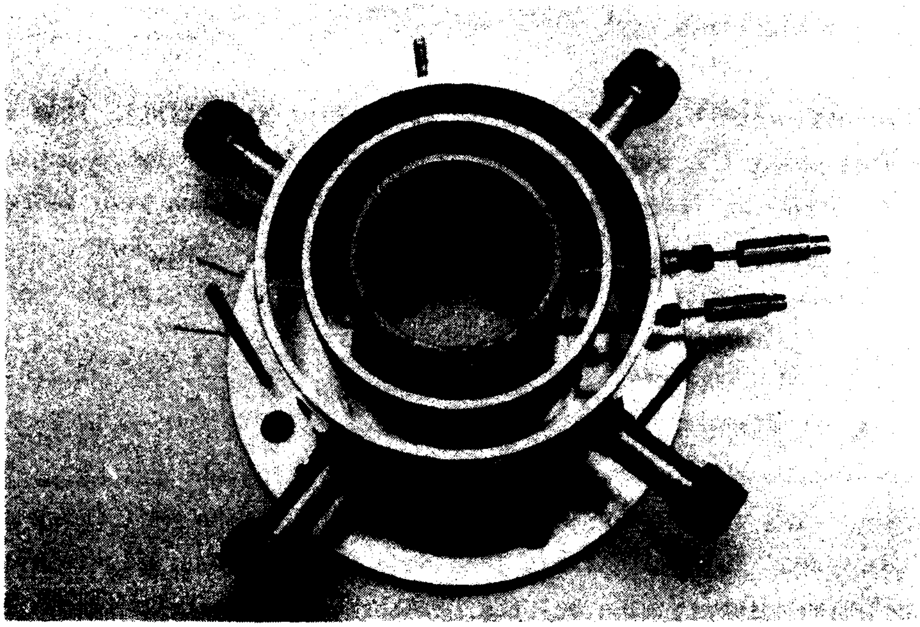

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Figure 3. End View of Segment

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Figure 4. Exploded View of Nozzle

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exploded view of the aft-end hardware. The AN fitting leads to the rotating valve. The cavity for collecting the flow to the rotating valve is also equipped with a Kistler pressure transducer.

Considerable attention has been given to generating a realistic flow environment. By sectioning the apparatus, the length-to-diameter ratio can be varied from 2 to 23; however, it is expected that primary interest will be between 9.5 and 23. This range encompasses the transition in velocity profile predicted by Beddini.[32] Table I shows the range of surface Mach numbers which can be investigated.

3.2 EXPERIMENTAL RESULTS

Experiments to date have concentrated on demonstrating the proper operation of the apparatus. The primary concern in this regard is the uniformity of the flow from each section. This effort has been concluded successfully as evidenced by the mean pressure distribution and the pressure drop measured across each segment. Table II shows these data. Note the pressure drop across the porous tubing is nearly constant for each segment. Note also the consistent drop in mean port pressure with increasing length. Since the flow to each section is constant, these data verify the near uniformity of the surface Mach numbers.

One measurement of oscillatory heat fluxes was also made, figure 5. The rotating valve generated a dimensionless acoustic pressure of 5.7×10^{-4} at 70 Hz, the fundamental acoustic mode of this particular configuration. Heat flux

TABLE I. RANGE OF SURFACE MACH NUMBERS

		L/D		
		9.5	16.6	23.7
	1.3	0.0017	0.001	0.0007
d_t	1.9	0.0035	0.002	0.0014
	2.27	0.007	0.004	0.0028

oscillations were measured at three axial locations using a gage overheat temperature of 250°C. Note that the maximum oscillation was observed at the L/D of 5.34 and that there is significant amplitude at the second harmonic. At an L/D = 14.8, no organized oscillations were observed. No interpretation of these data can be made until velocity and turbulence profile measurements have been made.

TABLE II. MEAN PRESSURES IN APPARATUS (HEAD-END PRESSURE = 40 PSIA)

Section Number	Pressure Between Flow Distribution and Porous Tubes, psia	Port Pressure Along Porous Tubing (Fraction of Section Length), psia		
		1/4	1/2	3/4
1	41.0	38.6	38.6	38.7
2	41.0	38.6	38.6	38.5
3	41.0	38.5	38.6	38.5
4	40.8	38.5	38.6	38.6
5	40.7	38.4	38.4	38.5
6	Tube blocked	38.3	38.2	38.3
7	40.4	38.1	38.1	38.0
8	40.6	38.1	37.9	38.0

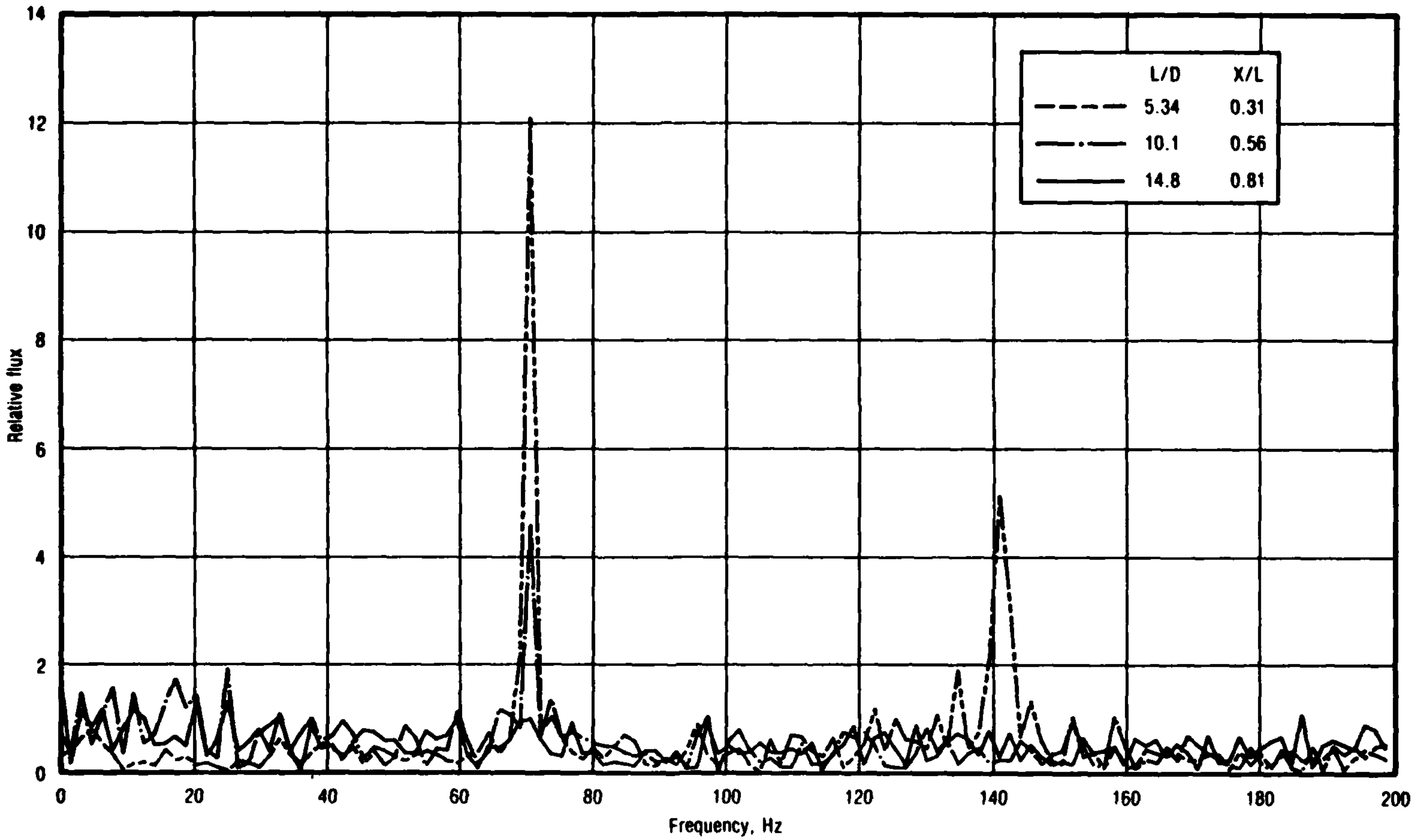

Figure 5. Oscillatory Heat Flux Driving at 70 Hz $(\epsilon')_{x=L} = 5.7 \times 10^{-4}$

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